DTU Library

Control of Single-room Ventilation with Regenerative Heat Recovery for Indoor Climate and Energy Performance

Smith, Kevin Michael; Svendsen, Svend

Published in:
CLIMA 2016 - Proceedings of the 12th REHVA World Congress

Publication date:
2016

Document Version
Peer reviewed version

Citation (APA):
Smith, K. M., & Svendsen, S. (2016). Control of Single-room Ventilation with Regenerative Heat Recovery for Indoor Climate and Energy Performance. In P. Kvols Heiselberg (Ed.), *CLIMA 2016 - Proceedings of the 12th REHVA World Congress* (Vol. 10)

Control of Single-room Ventilation with Regenerative Heat Recovery for Indoor Climate and Energy Performance

Kevin Smith[1], Svend Svendsen[2]

Department of Civil Engineering, Technical University of Denmark
Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark

[1]kevs@byg.dtu.dk

[2]ss@byg.dtu.dk

Abstract

The Danish government will seek energy-efficiency improvements to meet their targeted aims. Single-room ventilation with heat recovery allows simple installation through the façade and may be broadly deployed in apartments. Danish building regulations require greater than 80% heat recovery in new constructions and will soon require 85%. The development of single-room ventilation units may aim for these requirements as a result. The exhaust temperatures in highly efficient heat exchangers may approach outdoor levels. The cold exhaust cannot contain ample moisture, so vapour will condense on the heat exchanger. Available literature suggests that uncoated rotary heat exchangers transfer this condensate to the supply air, so the drying capacity of the ventilation system may be severely limited. This could raise indoor relative humidities to unsafe levels, which could promote the growth of dust-mites and mould. Controls may increase drying capacity by increasing ventilation airflow, but this may not be sufficient to limit moisture-related risks. This research investigated the added demand-control measure of reducing variable heat recovery to increase drying capacity when using an uncoated rotary heat exchanger in single-room ventilation. Simulations demonstrated that increased airflow sufficiently lowered the relative humidity in living rooms and bedrooms during most hours of the year. Decreased heat recovery was only necessary for a limited number of hours to maintain safe indoor relative humidities in these rooms, and the overall average reduction in heat recovery was less than 3%. The combined measures only succeeded in living rooms and bedrooms, and the results confirmed that rotary heat exchangers should not be used in kitchens or bathrooms, where moisture risks may be unavoidable.

Keywords - single-room ventilation; rotary heat exchanger; moisture issues; renovated buildings; energy retrofit

1. Introduction

The Danish government aims to completely rely on renewable energy sources for electricity and heating in buildings by 2035 [1]. Energy efficiency measures will help to achieve these aims. Therefore a Danish national energy efficiency action plan [2] expects to reduce heating consumption in buildings by at least 35% before 2050 compared to 2011. A report by the Danish Building Research Institute [3] established the strategy and scenario for these savings. Another scenario included technical advancements towards achieving 45% savings. The scenario required cost-effective deployment of mechanical ventilation with heat recovery on a broad scale. The report demanded inexpensive flexible new technologies for renovated buildings. It also required new knowledge and competence to properly implement these technologies.

Single-room ventilation with heat recovery may provide a flexible and affordable solution for new and renovated buildings. Its placement in the façade minimizes the ductwork, planning and installation-time necessary for implementation. It also provides inherently optimal and customizable service delivery to meet the needs of each room [4]. Recent research hoped to improve the cost, quality and efficiency of single-room ventilation with heat recovery. Smith and Svendsen [5] described a collaborative effort to develop a cost-effective single-room ventilation unit for renovated apartments in Denmark. The development aimed to meet a list of criteria, including 80% heat recovery efficiency (i.e. temperature efficiency) as required for new buildings. This resulted in a novel rotary heat exchanger made of a plastic honeycomb with small circular channels. Rotary heat exchangers are an example of regenerative heat exchangers (or regenerators). These periodically regenerate a heat transfer medium to store and recover heat. Alternating or fixed-matrix heat exchangers are also examples of regenerators, which may stop or slow their regenerative cycles to bypass heat recovery. This provides a means to control supply air temperatures and prevent frost accumulation. Regenerative heat exchangers also transfer condensate from the exhaust to the supply air even if they are not coated with desiccant. This removes the need for drainage, which could be necessary in a recuperative heat exchanger. These characteristics make regenerators appealing for use in single-room ventilation. However their behaviour in temperate humid conditions may be problematic if they transfer too much condensate from the exhaust to supply air as this decreases drying capacity. In the future building stock, buildings are increasingly airtight so the drying capacity of mechanical ventilation becomes ever more important. With highly efficient heat recovery, the drying capacity of a regenerator may be as small as the difference in moisture content between the saturated exhaust air and the nearly saturated outdoor air.

Smith and Svendsen [6] simulated single-room ventilation units in renovated Danish apartments. The results showed that efficient uncoated rotary heat exchangers recovered excessive moisture from kitchens or bathrooms (i.e. wet rooms) and yielded a substantial mould risk. Based on literature, the constructed moisture scenarios showed that vapour release is lower and less varied in living rooms and bedrooms (i.e. dry rooms), which reduces the risk of excessive moisture recovery with regenerators. The results suggested the possibility of a combined solution of single-room ventilation units that use recuperative heat exchangers (that do not recover moisture) in wet rooms and regenerative heat exchangers in dry rooms. This would match the type of heat recovery and its related drying capacity to the ventilation needs of individual rooms. It would also allow the units in wet rooms to drain to available plumbing while the units in dry rooms would not require drainage.

The present research used Matlab software to simulate the impact of demand-control on a rotary heat exchanger to achieve optimal indoor humidity. The rotary heat exchanger transferred condensate from the exhaust to the supply air, but this was controlled with variable flow rates and variable heat recovery based on values of indoor relative humidity. This research investigated the effect of a controlled decreased in heat recovery when maximum ventilation airflow was insufficient to remove moisture.

2. Methods

Apartment description

The simulated apartment represents a typical construction in Denmark. Its gross exterior area was 77 m2, which is the Danish average for social housing. An actual floorplan of a Danish apartment supplied the room sizes and layout for simulations, which is shown in Figure 1. Additionally, Figure 2 shows the weekday occupancy profile. Simulations assumed a total occupancy of two adults and one child in the apartment.

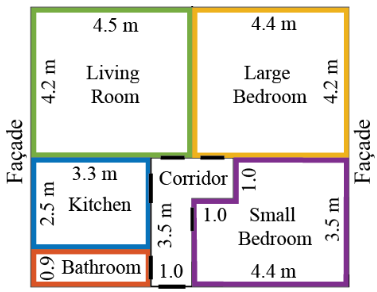

Figure 1. Layout of the apartment.

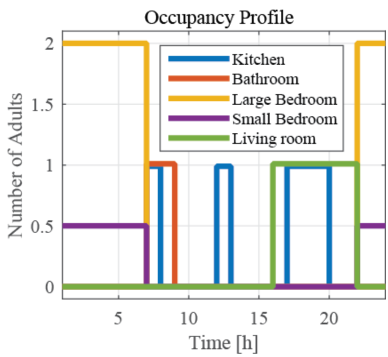

Figure 2. Weekday occupancy schedule.

Moisture balance equations

Smith and Svendsen [6] constructed three scenarios of vapour production in a typical one-family apartment based on available literature. The scenarios represented the best-, typical- and worst-case moisture release schedules to identify outcomes for a range of probable conditions. Table 1 shows the aggregated values. For comparison, Christian [7] listed the vapour production in a typical one family apartment as approximately 6-10 kilograms per day.

Table 1. Assumed aggregate values for the release of indoor moisture sources in the simulated apartment [6].

Activity	*Room*	Frequency	*Units*	Scenarios: Best-case	Scenarios: Typical case	Scenarios: Worst-case
Cooking load	*Kitchen*	-	*kg/day*	0.24	2.35	5.06
Dishwasher load	*Kitchen*	*daily*	*kg/day*	0.05	0.15	0.45
Cleaning	*All*	*weekly*	*kg/m2*	0.005	0.005	0.15
			kg/day	0.04	0.04	1.32
Shower load	*Bathroom*	3 *showers/day*	*kg/shower*	0.20	0.35	0.53
			kg/day	0.60	1.40	2.12
Clothes drying load	*Bathroom*	3 *loads/week*	*kg/load*	0	1.67	2.9
			kg/day	0	0.72	1.24
Plants	*Living*	*Continuous*	*kg/day*	0	0.06	0.45
Pets	*Living*	*Continuous*	*kg/day*	0	0.12	0.41
Occupancy	*Various*	-	*kg/day*	2.25	2.25	2.25
TOTAL	***All***	**-**	***kg/day***	**3.18**	**7.09**	**13.30**

Moisture limits

Several studies investigated moisture limits to prevent mould growth on surfaces. Rowan *et al.* [8] recommended a maximum local surface relative humidity of 75% to limit fungal growth. Johansson *et al.* [9] listed several limits above 75% based on material type and cleanliness. Vereecken and Roels [10] reviewed mould growth models and determined that many use critical surface relative humidities above 80%. An available ASHRAE standard also takes temporal effects into account using a moving average. Based on expert opinion and limited information [11] ASHRAE Standard 160:2009 [12] recommended a maximum 30-day moving-average surface relative humidity of 80% and a maximum 7-day average of 89%. Surface temperatures are uncertain and vary due to thermal bridges, which worsens the confusion on appropriate limits for indoor relative humidity.

Standard EN15251 [13] provides performance categories to assess the relative humidity (RH) of indoor air. This may be appropriate for simplified airflow simulations, as employed in this research, which may not accurately predict surface temperatures. The upper limits in categories I and III are 50% RH and 70% RH, respectively. Category IV is defined as being acceptable for a “limited part of the year”, so RH must only exceed 70% for a short duration. Furthermore, dust mites proliferate at relative humidities above 50% [14], so category I limits their growth. This is especially important in bedrooms and living rooms where textiles feed their growth. The results were therefore analysed with respect to these limits.

Simulations

Smith and Svendsen [6] described simplified simulations of moisture balance equations for single-room ventilation in a Danish apartment. Simulations used time steps of 10 minutes and calculated iterations in Matlab. The iterations took the form:

$$x_{room,i+1} = x_{room,i} + \frac{G_{room,i}}{(\rho V)_{room}} + N_{inf}\left(x_{amb,i} - min\{x_{room,i}, x_{sat,room}\}\right) + N_{vent,room,i}\left(x_{sup,room,i} - min\{x_{room,i}, x_{sat,room}\}\right). \quad (1)$$

where x is a moisture content in mass of water per mass of dry air, N is an air change rate per time step, G is a moisture release. The subscripts *room* and *i* represent the simulated room and time step index respectively, while the subscripts *inf*, *vent*, *amb*, *sat* and *sup* represent infiltration, ventilation, ambient, saturated and supply air, respectively. Smith and Svendsen [6] provided further details of variable calculations.

Ventilation

The simulated apartment assumed a new or renovated construction, so the infiltration rate complied with the 2015 Danish building regulations. The regulation [15] specifies a maximum infiltration rate of 1 L/sm^2 at a pressurization of 50 Pa. At a room height of 2.4 m, this equates to a limit of 1.5 air changes per hour at 50 Pa. Based on a rule-of-thumb [16], this corresponds to an infiltration rate of 0.075 air changes per hour at an average pressure of 4 Pa, so simulations assumed this value.

Simulations calculated the minimum ventilation rate for each single-room unit as 0.5 air changes per hour. The calculation used respective room volumes. This minimum is roughly similar to the minimum in the Danish building regulations of 0.3 L/sm^2. Simulations used a maximum ventilation capacity of 20 L/s and 15 L/s for the kitchen and bathroom, respectively, as required by Danish regulations. The adult bedroom and living room assumed a maximum ventilation rate of 14 L/s as specified by category II in EN 15251 to sufficiently dilute bio-effluents from two adults. The small bedroom assumed a maximum ventilation rate of 10 L/s, which is the category I requirement to dilute bio-effluents.

Demand-control

Prior simulations by Smith and Svendsen [6] modulated ventilation airflow from minimum to maximum capacity between 50% and 70% indoor RH in each room. This research altered those controls and decreased heat recovery when maximum ventilation airflow was insufficient to remove moisture. The simulation first determined the ventilation flow rate in each room based on its relative humidity, φ. The controlled increase occurred between 40% and 50% RH by the equation

$$N_{vent,room,i} = N_{vent,room,min} + \left[\left(N_{vent,room,max} - N_{vent,room,min}\right) \cdot min\left\{1, max\left\{\varphi_{room,i} - 40\%, 0\right\}/(50\% - 40\%\right\}\right]. \quad (2)$$

A decrease in heat recovery produces higher exhaust temperatures and greater drying capacity of ventilation air. The simulations decreased heat recovery for indoor relative humidities above 50%. Smith and Svendsen [5] experimentally demonstrated that slowing the regenerative cycle of a heat exchanger could decrease heat recovery. The simulation calculated the maximum temperature efficiency at a given flow rate using the model described in Smith and Svendsen [5] for a prototype rotary heat exchanger in single-room ventilation. This assumed a maximum rotational speed of 10 rpm. The simulation also determined the minimum temperature efficiencies required to provide adequate supply air temperatures and avoid cool draughts. The minimum supply air temperature was 15°C.

The decrease in temperature efficiency, η, was simulated between its minimum and maximum as

$$\eta_{room,i} = \eta_{room,max} - \left[\left(\eta_{room,max} - \eta_{room,min}\right) \cdot min\left\{1, max\left\{\varphi_{room,i} - 50\%, 0\right\}/(70\% - 50\%\right\}\right]. \quad (3)$$

3. Results

The results of simulations were plotted as annual duration curves, multi-day moving-averages, and hourly averages to assess the performance of regenerative heat recovery on various time scales.

Duration curves

Figure 3 shows the cumulative duration curves for the fraction of time steps above specified relative humidities during the heating season. In the kitchen and bathroom (i.e. wet rooms) the regenerative heat exchanger recovered excessive moisture and provided severe mould risk. In the worst-case scenario for moisture production, the regenerative heat exchanger provided saturated conditions for approximately half of the heating season in these rooms. The added drying capacity from the demand-based reduction in heat recovery was not enough to limit relative humidity and mould risk. The results confirm the conclusion that regenerative heat recovery must not be used in wet rooms as was previously shown by Smith and Svendsen [6].

It is clear from the plots that demand-control effectively removed moisture from the living room and bedrooms (i.e. dry rooms) with either type of heat exchanger. The slope of the duration curve sharply declined between 40% and 50% RH, which shows the effect of increased airflow. These results indicate that further demand-control with reduced heat recovery may not be necessary to avoid mould risk in dry rooms.

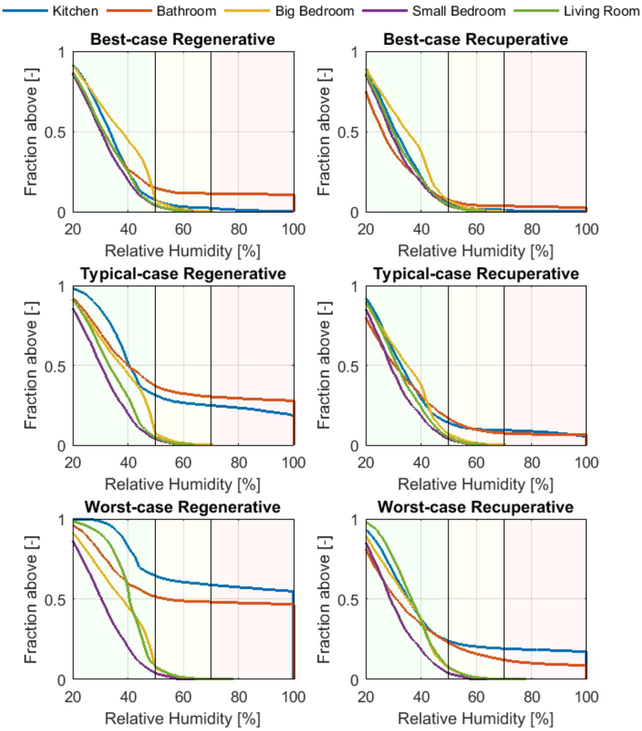

Figure 3. Duration curves of relative humidities in the heating season for the best-, typical- and worst-case scenario moisture production schedules.

7-day moving-averages

Figure 4 shows the results of 7-day moving-averages for indoor relative humidity, ventilation air change rate, and heat exchanger temperature efficiency. These plots can indicate seasonal differences and to what extent the demand-controls reduce indoor RH. The figure shows the results of simulations with the worst-case moisture production scenario.

Increases in ventilation airflow and reductions in heat recovery consume added energy. However the results show that the difference is minor between regenerative and recuperative heat exchangers in dry rooms. The average difference in ventilation air change rate is less than 0.14 per hour in the adult bedroom and less than 0.07 per hour in the other dry rooms. Similarly, the average difference in temperature efficiency is less than 3% in the adult bedroom and less than 1.5% in the other dry rooms.

The 7-day moving-average RH rarely surpassed 50% in dry rooms. This would meet category I of EN 15251, and it is substantially less than the ASHRAE limit of 89% for 7-day surface RH. The results also show low seasonal variability in dry rooms with either type of heat exchanger, which could not be identified from the duration curves.

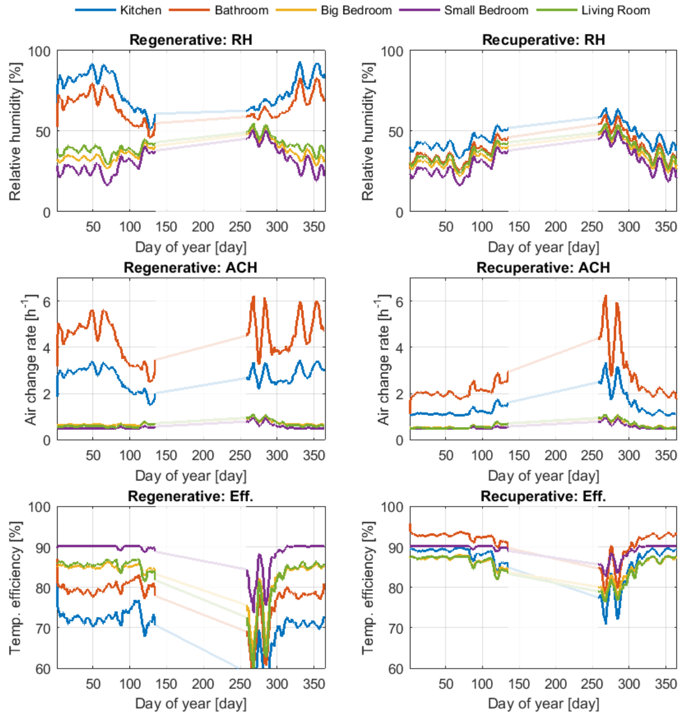

Figure 4. 7-day moving-average relative humidities, air change rates (ACH), and temperature efficiencies throughout the heating season with regenerative and recuperative heat exchangers and the worst-case moisture production scenario.

50th-day hourly time-series

Figure 5 shows the hourly time-series data on day 50 (i.e. February 19th) of the simulation with the worst-case moisture production scenario. The previous figure indicated that day 50 had particularly high relative humidity and warranted further inspection. With the regenerative heat exchanger the maximum ventilation airflow in the living room and adult bedroom did not remove enough moisture to limit RH to below 50%. This activated the proportional controller that decreased the temperature efficiency of the heat exchanger and increased drying capacity. This successfully limited the relative humidity in these rooms to near 50%. As previously indicated by Figure 4, these brief reductions in heat recovery had a limited impact on the overall average temperature efficiency, which still met Danish regulations. The simulations did not reduce heat recovery in the recuperative heat exchanger as this would not increase drying capacity. It therefore provided a baseline for comparison.

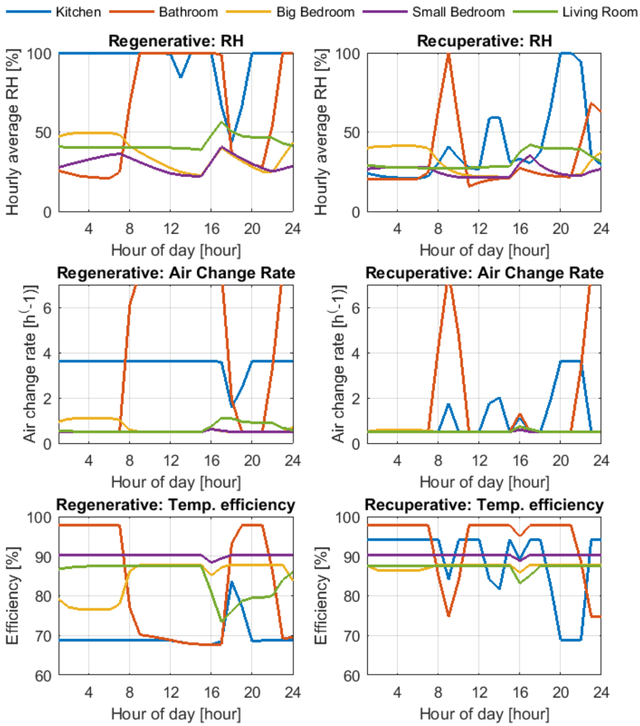

Figure 5. Hourly time-series data of relative humidities, air change rates (ACH), and temperature efficiencies using regenerative or recuperative heat exchangers on the 50th day.

4. Discussion and Conclusion

Building materials did not buffer indoor humidity in simulations. Buffering would have dampened extreme values of indoor humidity and lessened the time above the specified limits. Salonvaara *et al.* [17] and Mortensen *et al.* [18] determined that interior paints often behave as vapor barriers and limit moisture transfer between construction materials and room air. Therefore it was reasonable to assume that construction materials did not buffer indoor RH.

The simulation also assumed that other materials, such as furniture and textiles, did not dampen indoor humidity. Svennberg *et al.* [19] furnished a room and measured a 10% lower daily peak in room RH, so this buffering may be significant. However, the simulations of regenerative heat recovery yielded nearly flat duration curves above 50% RH, as shown in Figure 3. Therefore, a 10% decrease in peak RH (i.e. a leftward shift of the curve) would not impact the conclusion of too high moisture risk in wet rooms.

The results indicated that regenerative heat recovery may be suitable for single-room ventilation of dry rooms in Danish apartments. The simulation of demand-controlled ventilation and variable heat recovery demonstrated its potential to minimise moisture risk. Increased airflow alone may be sufficient to limit moisture risk in dry rooms, but variable heat recovery provides a secondary option to ensure minimal risk. The increased drying capacity from reduced heat recovery was only necessary for a limited number of time steps during the year. The total decrease in heat recovery was less than 3% in the adult bedroom and less than 1.5% in other dry rooms. The demand-controls did not remove enough moisture from wet rooms when using regenerative heat recovery, so the use of regenerators should be prohibited in these rooms.

Acknowledgment

This research was funded by The Market Development Fund (Markedsmodningsfonden) and the Technical University of Denmark to research decentralized ventilation for use in renovations of existing residential apartments.

References

[1] Energi Styrelsen, Energistatistik 2014 [Energy statistics 2014], Copenhagen, 2014.
[2] Danish Energy Agency, Denmark's National Energy Efficiency Action Plan, Copenhagen, 2014.
[3] Dansk Klima-, Energi- og Bygningsministeriet, Strategi for energirenovering af bygninger [Strategy for energy renovation of buildings], Copenhagen, 2014.
[4] D.R. Wulfinghoff, Multiple-zone HVAC: An obsolete template, World Energy Eng. Congr. 2009, WEEC 2009. 2 (2008) 762–768. doi:10.1080/01998595.2011.10389019.
[5] K.M. Smith, S. Svendsen, Development of a plastic rotary heat exchanger for room-based ventilation in existing apartments, Energy Build. 107 (2015) 1–10. doi:10.1016/j.enbuild.2015.07.061.
[6] K.M. Smith, S. Svendsen, The effect of a rotary heat exchanger in room-based ventilation on indoor humidity in existing apartments in temperate climates, Energy Build. *In process*. doi: 10.1016/j.enbuild.2015.12.025.
[7] J.E. Christian, Moisture Control in Buildings: The Key Factor in Mold Prevention—2nd Edition, ASTM International, West Conshohocken, PA, 2009. doi:10.1520/MNL18_2ND-EB.
[8] N.J. Rowan, C.M. Johnstone, R.C. McLean, J.G. Anderson, J. a Clarke, Prediction of toxigenic fungal growth in buildings by using a novel modelling system., Appl. Environ. Microbiol. 65 (1999) 4814–21.

[9] P. Johansson, I. Samuelson, A. Ekstrand-Tobin, K. Mjörnell, P.I. Sandberg, E. Sikander, Extracts from Microbiological growth on building materials, SP Technical Research Institute of Sweden, Borås, 2005.
[10] E. Vereecken, S. Roels, Review of mould prediction models and their influence on mould risk evaluation, Build. Environ. 51 (2012) 296–310. doi:10.1016/j.buildenv.2011.11.003.
[11] A. Tenwolde, A review of ASHRA standard 160 - Criteria for moisture controle design analysis in buildings, J. Test. Eval. 39 (2011) 1–5. doi:10.1520/jte102896.
[12] ASHRAE Standing Standard Project Committee 160, Addendum A to ANSI/ASHRAE Standard 160-2009, ASHRAE, Atlanta, 2011.
[13] European Committee for Standardization, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, EN 15251:2007, Brussels, Belgium, 2007.
[14] L.G. Arlian, Water balance and humidity requirements of house dust mites, Exp. Appl. Acarol. 16 (1992) 15–35. doi:10.1007/BF01201490
[15] Danish Energy Agency, Building Regulations, Copenhagen, 2015.
[16] M.H. Sherman, Estimation of infiltration from leakage and climate indicators, Energy Build. 10 (1987) 81–86. doi:10.1016/0378-7788(87)90008-9
[17] M. Salonvaara, T. Ojanen, A. Holm, H. Kunzel, A. Karagiozis, Moisture buffering effects on indoor air quality – experimental and simulation results, Proc. Perform. Exter. Envel. Whole Build. IX (2004) 1–11.
[18] L.H. Mortensen, C. Rode, R. Peuhkuri, Full scale tests of moisture buffer capacity of wall materials, Proc. 7th Symp. Build. Phys. Nord. Ctries. (2005) 662–669.
[19] K. Svennberg, L.G. Hedegaard, C. Røde, Moisture buffer performance of a fully furnished room, Proc. Perform. Exter. Envel. Whole Build. IX (2004) 1–11.